

Twisting biomaterials around your little finger: environmental impacts of bio-based wrappings

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Received: 13 May 2009 / Accepted: 3 January 2010 / Published online: 25 March 2010
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Abstract

Background, aim, and scope Packaging uses nearly 40% of all polymers, a substantial share of which is used for sensitive merchandise such as moisture-sensitive food. To find out if bio-based materials are environmentally advantageous for this demanding application, we compared laminated, printed film across the whole life cycle.

Materials and methods We compared bio-based materials (paper, polylactic acid, bio-based polyethylene, and a bio-based polyester) as well as conventional ones (polypropylene, polyethylene). Data stemmed from 13 companies that produce raw materials, films and/or laminates and which co-operated with us in a project commissioned by a large food producer. The functional unit chosen for this study is 1 m² of packaging film. This is (mostly) laminated, printed film that is delivered on reels to the food industry, where the laminate is cut, sealed and filled. The impact assessment is presented for non-renewable energy use, total energy use, global warming potential, depletion of abiotic resources, photo-oxidant formation, acidification, eutrophication, water use, and land use.

Results For Inner Packs that get in direct contact with food and therefore require certain barrier properties, the environmental performance of many laminates is not better than the reference, petrochemical material. However, our study shows that paper/polypropylene laminates perform equally well as the current material (polypropylene) if the material is landfilled, and better if incinerated with energy recovery. For Outer Packs, bio-based polyethylene film shows a particularly low environmental impact. Paper/bio-based

polyester laminates also offer significant savings compared with the current material. For Inner as well as Outer Packs, laminates including polylactic acid offer environmental advantages when accounting for wind credits or when assuming a future technology level for polymer or film production.

Discussion Increased technology maturity of PLA and cellulose in the film production stage offers significant environmental improvement with respect to global warming potential compared with today's technology. Though large, the uncertainty regarding the degree of degradation of paper, cellulose, PLA and bio-based polyester, is not decisive for the conclusions.

Conclusions and recommendations Generally, laminates and films (partly) consisting of bio-based polymers offer opportunities for significantly reducing environmental impacts of food packaging. Large variations in land-use are possible depending on the type of bio-based material that is used. The environmental advantages differ depending on the polymer and the final product (Inner vs. Outer Pack). Lack of experience and investment in converting bio-based polymers into final products and comparatively unfavourable material properties result in lower environmental advantages for some novel bio-based materials than one may expect. However, a) already today, the options with the lowest global warming potential are partly or fully bio-based and b) bio-based materials will benefit more from technological progress than conventional materials, potentially making certain bio-based laminates highly attractive options for the future. Overall, Outer Packs are more promising than Inner Packs when introducing bio-based wrappings to replace the current petrochemical material because a) the opportunities are clearer for this application and b) the product specifications (required barrier properties) are less demanding. Starting with the Outer Packs would also

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allow bio-based polymer producers and processors to invest and learn, thus offering the opportunity to reduce the environmental impact even further.

Keywords Biomaterial · Biopolymer · Cellulose · Film · LCA · Life cycle assessment · Packaging · Paper · Plastic · Polyester · Polyethylene · Polylactic acid · Polypropylene

Abbreviations

ADP	abiotic depletion potential
AP	acidification potential
AlO _x	aluminium oxide
BBP	bio-based polyester (not further specified upon request of producer)
EP	eutrophication potential
EVA	ethyl vinyl acetate
GHG	greenhouse gas
GWP	global warming potential
H2O	water use (impact category), consisting of process, cooling and irrigation water
MOPP	metallised oriented PP
MPET	metallised PET
MPLA	metallised PLA
NREU	non-renewable energy use
OPP	oriented PP
PE	polyethylene
PET	polyethylene terephthalate
PLA	polylactic acid
POF	photochemical oxidant formation
PP	polypropylene
PUR	polyurethane
PVdC	polyvinylidene chloride
R&D	research and development
REU	renewable energy use
SiO _x	silicone oxide
TEU	total energy use (NREU+REU)

1 Background, aim, and scope

The first man-made polymers were derived from biomass resources, but since the 1930s petrochemical polymers have gradually displaced them during the growth of the petrochemical industry. Since the 1980s and especially during the 1990s, bio-based polymers have experienced a comeback, with the main drivers being the limited volume of landfill capacity and the bad general image of plastics and other packaging materials as well as the high oil price, the rapid progress in biomass-based processes (e.g. white biotechnology) and the outstandingly good public perception of bio-based polymers (Käb et al. 2002; Patel et al. 2006). In the EU25 plus Norway and Switzerland, 37% of

all plastics or 18.3 million tonnes went into packaging in 2006 (PlasticsEurope 2008), thus indicating this sector's importance. It is a market that has been dominated by petrochemical plastics, most notably by polyethylene (PE) and polypropylene (PP). However, in light of the comeback of bio-based polymers in general, the packaging market and the producers of food and consumables are increasingly discovering the opportunities of bio-based packaging materials. Their use can offer new waste management strategies for packaging, e.g. through compostable wrappings that may reduce the pressure of household waste on landfills¹ and may improve public perception of the product.

Key bio-based materials with potential applications in the packaging sector are paper, starch, cellulose, polylactic acid (PLA) and other bio-based polyesters. Some of these materials have been used and produced for a long time (e.g. paper), others only for a short time on industrial scales (e.g. PLA). In the context of long-term emission targets, one of the important issues is to what extent bio-based materials score better in environmental terms compared to petrochemical polymers. Several studies have already been carried out regarding the environmental advantages or disadvantages of using novel biopolymers such as PLA (Vink et al. 2003; Vink et al. 2007), bio-based polyethylene (Hermann et al. 2007) or polyhydroxyalkanoates (Kim and Dale 2005a), concluding that there are environmental advantages for some bio-based materials and that other materials could become advantageous if technologies used in their production improve and progress. So far, these studies have focussed on comparing quantities of materials (e.g. 1 kg of PLA with 1 kg of conventional plastics). This study goes one step further and considers the functionality of these materials for a specific application: we focus on the production of a film or laminate for snack food packaging as a case study. No public literature is yet available on an environmental assessment of this specific application.

Some of the bio-based materials are known to have lower barrier properties for water and oxygen, and may therefore require thicker material layers or additional layers supplying barrier functions when used for packaging purposes. But do extra material requirements and less experience in processing these materials outweigh the environmental advantages of using bio-based materials in packaging and if so, to what extent? Which combination of materials, consisting at least partly of bio-based materials, can substitute synthetic polymers to a considerable degree

¹ In the EU25, two-thirds of all municipal waste is still being landfilled (Eurostat 2008).

in the short term future? To answer these questions, we carried out a life cycle assessment (LCA) in co-operation with industrial film producers and suppliers.

2 Methodology

2.1 Functional unit and system boundaries

The functional unit chosen for this study is 1 m² of packaging film. This is (mostly) laminated, printed film that is delivered on reels to the food factory, where the laminate is cut, sealed and filled. Cutting of the sheets and sealing and filling of the bags are excluded from the analysis because this step can be assumed to be identical across all packs of the same size and function, and to produce the same level of waste. The results of the environmental assessment are reported both for the system ‘cradle-to-factory gate’ (CF) and for the system ‘cradle-to-grave’ (CG): The system CF includes all activities in the process chain starting from the extraction & processing of non-renewable resources (e.g. oil and gas) or agricultural & silvicultural production (e.g. maize from seeds, including fertiliser and machinery use) up to and including film production, lamination and printing; it also covers all transportation activities and treatment of any process waste up and until the laminated film is delivered on reels to the food producer. The system CG includes the system CF plus waste management of the post-consumer packaging waste² where all key options are studied, i.e. incineration (with and without energy recovery), landfilling, composting, and digestion. We calculate GWP for the system cradle-to-factory gate for all bio-based products by adding all emissions of fossil greenhouse gas emissions and subtracting the biogenic carbon that is physically embedded in the product. As a consequence, both fossil and biogenic emissions of greenhouse gases from the waste treatment stages are considered.

2.2 System expansion

In this study, we applied system expansion (also referred to as ‘avoided burdens’) to account for the co-generation of electricity and heat. To determine the credit, electricity that is co-produced, e.g. during the incineration of waste, is assumed to replace electricity produced according to the average power generation in Europe (see Section 3.3) and

heat is assumed to replace average production in a gas-fired boiler.

2.3 Environmental impact assessment

In this study, we used the CML 2 baseline 2000 method (Guinée et al. 2001) for calculating the mid-point results, adding water use and land use as impact categories. For CF, the so-called LCA mid-point results are presented for the following impact categories: Non-renewable energy use, Total energy use (total of non-renewable and renewable energy use), Global warming potential, Depletion of abiotic resources, Photo-oxidant formation, Acidification, Eutrophication, Water use, and Land use;³ for CG, only results for the categories Non-renewable energy use and Global warming potential are shown because of the large uncertainties related to estimating individual process emissions other than CO₂, CH₄ and water during the waste treatment phase, especially of novel materials such as polylactic acid (PLA).

So far, water use as an impact category has not been very common in LCA studies but is receiving more and more attention (Mila i Canals et al. 2009; Pfister et al. 2009). Within the category of water use, we consider process water, cooling water and irrigation water. Process water includes all the water used during the production of raw materials, films and laminates but excludes the water used for electricity production from hydropower. The subcategory cooling water includes water used for cooling in any of the process steps. Irrigation water means water fed to the agricultural system during crop growth; it excludes rainfall because there is no generally accepted methodology that would allow a consistent comparison of rainfall quantities across agricultural as well as silvicultural crops and across geographical regions of production.⁴ Energy consumption for irrigation is excluded because it only contributes to a small extent to the total energy consumption of agricultural crops (Mila i Canals 2003).

Land for agriculture and forestry will be increasingly important in the future because of increasing land requirements not only for the production of food and feed but also

² The use phase is not taken into account because the direct impacts of packaging in the use phase are negligible (no significant release of compounds from the packaging to the environment in retail and in households).

³ We exclude results for toxicity primarily because of limitations of available data. Other reasons are doubts about the quality of toxicity calculations in LCA assessment tools, caused by the lack of reliable toxicity assessment models (see Dreyer et al. 2003; Guinée et al. 2001; Gustafsson and Börjesson 2007). We exclude results for stratospheric ozone depletion, which is not relevant any more since the phasing out of chlorofluorocarbons as a result of the Montreal Protocol.

⁴ For example, the FAO’s CROPWAT model only applies to agricultural crops.

of bio-energy, bio-fuels, and bio-materials. A growing number of environmental assessments of bio-materials include land use in their analyses (see Dornburg et al. 2003; Hermann et al. 2007; Kim and Dale 2005b) and methodological work is under way (see e.g. Jolliet et al. 2003; Kloverpris et al. 2008; Mila i Canals et al. 2007) but has not yet established one single accepted methodology in terms of how different types of land use should be compared. In this study, we focus on land use for agriculture and for (sustainable) forestry. The different types of land use (e.g. agriculture and forestry) are aggregated 1:1. The rotation period of forestry is taken into account. Land use for industrial plants, transportation infrastructure and waste management is comparable for different types of material and thus not taken into account.

2.4 Methodological problem: how to incorporate ‘green electricity’?

As can be observed among private consumers, companies are also increasingly purchasing ‘green electricity’ in order to reduce their environmental footprint; one such company is NatureWorks, the most important producer of PLA. Purchasing green electricity is an option for any producer - and this raises the question if such environmental credits should be considered when conducting an LCA. In order to describe the different views, we distinguish between the company perspective and the technology perspective. An LCA carried out from a *company perspective* includes not only the processes operated by the company itself but also the purchasing decisions the company makes regarding materials and energy inputs. As a consequence, a study using the company perspective gives credits for the avoided environmental burden related to green electricity. We argue that the company perspective should be applied for decisions concerning business relations. A comparison from a *technology perspective* of materials production and processing strives to eliminate the effect of whether the company uses power generated by using wind energy, natural gas or coal, focussing instead on the core technology. (Here, core technology refers to the production of materials and their subsequent processing to produce packaging film, but excludes the generation of green power as an optimisation strategy.) The technology perspective is the adequate choice when making decisions concerning material choice or R&D strategies. In this paper, we focus on the technology perspective because we are mainly interested in material choice; but we include a case of company perspective to show the difference between the two.

In the following, we describe the effect of a company’s decision to purchase ‘green electricity’, using the example of wind energy. The accounting practice adopted by the

International Energy Agency (IEA 2003) for their energy balance tables is that the primary energy form should be the first energy form downstream in the production process for which multiple energy uses are practical. The application of this principle leads to the following primary energy forms: 1) Heat for nuclear electricity, for geothermal heat or electricity and for solar heat production 2) Electricity for hydro, wind, wave/ocean and photovoltaic electricity production. This convention has been agreed upon internationally for energy balances. As there is no such agreement for LCAs in general, we follow the IEA convention. As a consequence, the primary energy consumption related to the production of 1 kWh of electricity is lower if it is generated from hydropower, wind, wave/ocean and/or photovoltaics compared to its generation from fossil resources (oil, gas, coal) or nuclear, geothermal or solar heat.

PLA is the only material in this LCA for which renewable energy credits were bought (starting in 2006). As shown in Table 1, moving towards wind energy in 2006 meant replacing 23 MJ/kg PLA of primary fossil energy by 6 MJ/kg PLA primary renewable energy. The total primary energy use decreased from 77.3 MJ/kg PLA to 60.3 MJ/kg PLA without any change in technology or secondary energy use and therefore solely as a consequence of the accounting practice for wind energy. The wind credits also have a large influence on impact categories other than energy use, most notably global warming potential, abiotic depletion and acidification.

3 The laminates and their production

3.1 Laminates studied

This study got the producers of the raw materials and semi-finished products as well as the producers of the packs in their final form (printed laminates) involved for the first

Table 1 Renewable energy use (REU) and non-renewable energy use (NREU) for the production of 1 kg of polylactic acid (PLA) with and without wind energy credits, derived from Vink et al. (2007)

		PLA 2005	PLA 2006
		technology	company
Wind credits		no	yes
NREU	MJ/kg	52.0	29.0
REU	MJ/kg	25.3	31.3
Total	MJ/kg	77.3	60.3

time in order to provide data and review the results.⁵ The films and laminates that are considered in this study were selected in collaboration with a multinational food producer and its film suppliers and converters. Criteria for selection were 1) that films and laminates consisted at least in part of bio-based materials and 2) that they were proven or expected to have comparable barrier properties as the currently used materials. In total, 32 alternatives were studied; of these 32 options, 17 represent ‘Inner Packs’ and 15 are ‘Outer Packs’. Inner Packs are in direct contact with the food and need to provide water and oxygen barriers. The targets are $<0.3 \text{ g m}^{-2} \text{ day}^{-1}$ moisture vapour transmission rate (MVTR) and $<30 \text{ cm}^3 \text{ m}^{-2} \text{ day}^{-1}$ oxygen transmission rate (OTR) respectively.⁶ Outer Packs serve as containers (bags) for the Inner Packs, therefore have no direct food contact and require no barrier function. The options studied are shown in Table 2 and the distribution of weight across the different types of materials in Fig. 1. The majority of the films and laminates are at various stages of development, from conceptual development to small-scale test production and are compared with the currently used reference material. Throughout the text we distinguish between films, which consist of one material (e.g. only PP), and laminates, which consist of multiple layers of materials (e.g. PP and paper). In order to make best use of the properties of the various materials, most of the packaging films are multi-material laminates. We consider laminates consisting practically only of bio-based materials, only of petrochemical materials or hybrid films consisting of both petrochemical and bio-based materials. As a consequence, only some of the novel material composites studied are biodegradable (marked with an asterisk in Table 2). The influence of the metallised layer (aluminium, aluminium oxide or silicon oxide) is minimal in composting: the weight of such a layer is usually much less than 1%, thereby fulfilling requirements of composting certification (EN 13432) and there are several metallised biodegradable films on the market that are certified compostable.

3.2 Data sources

The companies involved were supplied with surveys on the inputs and outputs regarding that part of the production process which takes place at their respective production sites. The data they provided was on the level of process inputs (materials and energy) and outputs (materials, waste

Table 2 Laminates included in this study, biodegradability is indicated by an asterisk. Reference materials are 1a and 1b for Inner Packs and 5a and 6 for Outer Packs. For Inner Packs: PP laminates are 1, PP hybrids are 2, PLA laminates are 3, paper laminates are 4. For Outer Packs: PE films are 5, PP film is 6, PLA film is 7, cellulose films are 8 and paper laminates are 9

No.	Material type	No.	Material type
1a	OPP / PE / MOPP	5a	PE
1b	OPP / PE / MOPP	5b	Bio-based PE
2a	Paper / PE / MOPP	5c	Bio-based PE
2b	Cellulose / PE / MOPP	6	OPP
2c	PLA / PE / MOPP	7*	PLA
3a	MPLA / PLA / PLA	8a*	Cellulose
3b*	PLA / AlO _x coated PLA	8b*	Cellulose
3c*	PLA / SiO _x coated PLA	9a	Paper / OPP
3d*	PLA SiO _x coated / SiO _x coated PLA	9b*	Paper / PLA
3e*	MPLA / MPLA	9c*	Paper / PLA
4a*	Paper / SiO _x coated PLA / PLA	9d	Paper / PE
4b	Paper / Aluminium / PLA	9e*	Paper / BBP ^a
4c	Paper / MPET / peelable ^b PP	9f*	Paper / BBP
4d	Paper / MPET / peelable PE	9g*	Paper / BBP
		9h	Paper / EVA

^a A bio-based polyester, material not further specified upon request of the producer.

^b Peelable means that this layer can easily be removed, manually, from the laminate.

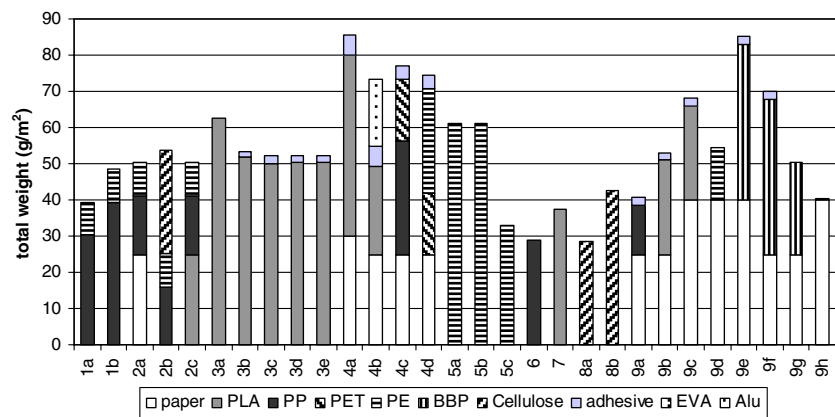
and emissions). We then went on to perform a plausibility check and to benchmark the received data against other company data as well as database data (where available). When large discrepancies were found, feedback was provided to the company. In some instances this led to a correction of the material inputs or outputs, but in other cases there was a technical explanation for certain differences. This resulted in a consistent data-set which was then incorporated in our calculations. At the end of the project and before submitting the final results, all contributors to the data-sets received a copy of the preliminary report and an opportunity to give feedback.

It is important to note that despite all these efforts, there can still be substantial differences between individual production sites, which are caused by differences in the quality of data or the level of technology. In the first case, data quality varied because only some of the suppliers had individual meters installed to measure energy consumption by individual process steps of the entire production process. Most suppliers broke down data from an entire production site or from the average yearly use of an installation to individual films or laminates. In the second case, the level of technology can lead to higher energy use for novel materials compared with ‘conventional’ films for the following reasons: 1) old production lines may be used

⁵ The names of the companies involved are not disclosed and only generic names are used for the various components of laminates.

⁶ Testing carried out subsequent to this analysis has shown that films 3b and 3c do not fulfill the required barrier properties.

Fig. 1 Total weight of films and laminates (Inner and Outer Packs), compare list of abbreviations



for small scale production of these films and, in general, these production lines are less energy-efficient than state-of-the-art production lines as used for current conventional materials, and 2) production processes for conventional materials have been fine-tuned over decades, leading to higher throughput, yields and/or energy efficiency of production. Both cases apply especially to novel materials that have not yet been converted into films on a large scale and where, as a consequence, fine-tuning has not yet occurred. We took this inherent bias in the data into account in a sensitivity analysis (see Section 5.1).

3.3 Location of production

We distinguished two levels of specificity, i.e. producer-specific⁷ data and regional (supranational) data. Producer-specific data was collected from production sites and can be grouped into information on materials production and processing. Producer-specific data was used for some polymers in primary form (e.g. PLA) and regional data for others (e.g. PP) and similarly for polymer processing such as the production of films from these materials. For example, regional data was used for OPP film but producer-specific data for PLA film because worldwide, there is only one large-scale plant to produce PLA. Similarly, also cellulose films for food packaging (using a novel technology) and a specific bio-based polyester (BBP) represent very specific products that are currently being produced at one or very few locations only. All these materials are novel and unique, the technology is not widely available and considerable progress can be made from one year to another. For paper we also used producer-specific data because of the multitude of different types of paper and their related LCA profiles, which make it difficult to decide which of the existing data sets are representative. On the other hand, bulk materials such as PP granulate are generally

purchased from a wide range of sources, nationally and internationally, and therefore no close link exists to a specific producer or production site.

Producer-specific data were used for:

- production of polylactic acid (PLA, Vink et al. 2007) and bio-based polyesters (BBP; these are complete life cycle inventories and therefore include producer-specific data on process inputs and outputs, including electricity)⁸
- generation of electricity and heat for the production of PLA and bio-based polyesters, for which there is only one producer each and therefore the respective local electricity profile was used (e.g. producer-specific power production in the USA was assumed for PLA)
- process inputs and outputs for the production of paper (includes producer-specific consumption of energy but draws on regional data for the electricity mix, see below)
- process inputs and outputs for the production of silicon oxide (SiO_x) from silica sand
- process inputs and outputs for the metallisation of films (with Al, AlO_x or SiO_x)
- process inputs and outputs for the polymer processing to produce films and adhesive layers from polymer granules
- process inputs and outputs for the lamination and printing processes.

Regional data were used for

- generation of electricity for which we assumed the average European mix⁹ of power generation for fuel types as well as efficiency (SimaPro 2007)

⁷ Sometimes also referred to as 'site-specific data'.

⁸ Grid electricity in the USA and Italy has comparable or larger environmental impacts than the European average, so the fact that these inventories do not use the European average does not benefit these materials.

⁹ Mix of UCTE (65%), CENTREL (9%), UK (12%) and Ireland (1%), shares of countries are proportional to their relative total production; GWP is 0.148 kg CO₂/MJ_{el}.

- production of process heat for which we assumed an estimated average efficiency and fuel mix for Europe (with the exceptions just explained for power; SimaPro 2007)
- production of standard petrochemical polymers, namely polypropylene (PP, as granulate and oriented film)¹⁰, polyethylene (PE), polyethylene terephthalate (PET), polyvinylidene chloride (PVdC) and polyurethane (PUR, used as adhesive) as well as ethyl vinyl acetate (EVA) for all of which we made use of data-sets that represent a European average (Boustead 1999–2005)
- production of inorganic compounds, in particular aluminium (Al), and aluminium oxide (AlO_x) for which we used European averages (SimaPro 2007)
- transportation by road, rail and ship for which we assumed European averages (SimaPro 2007); for rail additionally also a US average for the transportation of PLA to the harbour was included.
- waste management by composting, digestion, land-filling, and incineration (see Section 3.5)

All regional data (such as electricity, heat, plastic granulate production) were assumed for a European setting, with the exception of PLA raw material produced in the USA and transported to Europe. Technical specifications such as tie layer thickness in extrusion lamination also vary among regions. Results were therefore only calculated for packs used and produced in Europe and may not be identical, nor lead to the same conclusions for the USA, Asia or other regions.

3.4 Transport of materials

Transportation was considered during all stages of production, i.e. from the transportation of raw materials (such as wood for paper) to the delivery of laminates to the food producers. All manufacturing activities (production of materials, films and laminates) were assumed to occur within Europe, with the exception of PLA granulate production, for which the only large-scale industrial process is located in the U.S. As a consequence, the transportation distances and therefore also the environmental impacts from transportation are much larger for PLA than for the other materials.¹¹ Generic, regional data-sets were used for transport by lorry, rail and

ship. Lorries were assumed to have a total maximum weight of 40 tonnes and a conservative load factor of approximately 50%. Ships were also considered to transport loads in large quantities and over long distances. Trains were assumed to run predominantly (70%) on electricity in Europe. A separate data-set was used for the transportation of PLA by train in the USA with higher primary energy use to account for lower energy efficiency.

3.5 Post-consumer waste collection and treatment

Compared to the impacts of material production, transportation generally causes comparatively small environmental impacts. Due to the short collection distances this is particularly the case for collection & transportation of mixed household waste (including Inner and/or Outer Packs) in municipalities and their surroundings. We therefore excluded post-consumer waste collection from the LCA calculations. For all post-consumer waste treatment options, readily available data from databases and publications were compiled per type of material embodied in the waste. Based on this available information and additional input by experts from the field, we estimated the water and carbon released (as carbon dioxide or methane) from the material during the waste phase for all materials (Hermann and Patel 2007). For landfilling, composting and digestion, values in literature diverge significantly with respect to the carbon released over time (see e.g. 0–100% for PLA in landfill in Bohlmann 2004, 55% for composting of PLA in Iovino et al. 2008, 80% for composting of PLA in Kale et al. 2007). We take this uncertainty into account through uncertainty ranges for the degradation levels of these materials, i.e. high and low carbon storage (resp. low and high level of degradation, see Figs. 4 and 7).

4 Results

4.1 Inner packs

As Fig. 2 shows, the reference material OPP films (No.1a and 1b) are among the best or the best for total energy use (TEU), photochemical oxidant formation (POF), acidification (AP) and eutrophication (EP). The paper/OPP film (No.2a) is a more favourable option than the reference materials: it scores at least equally well as the reference material for all environmental indicators except for water use (H₂O) and eutrophication. In terms of global warming (GWP) and non-renewable energy use (NREU), Figure 2 shows that a PLA-based laminate with wind credits (No.3bw) is comparable with the reference cases (No.1a and 1b) and somewhat less attractive than the paper hybrid (No.2a). The results for land-use are shown in Fig. 3.

¹⁰ Oriented film data was checked with industry, and the values for cooling and process water use during oriented film production were corrected.

¹¹ Exact transportation routes as well as exact load factors are difficult to model because they frequently change: all suppliers involved in the project use a hauling system, where the haulier determines the exact route depending on other goods that may be transported in the same container. We have therefore assumed direct routes but low load factors (i.e. an empty return trip), based on the understanding that a higher load factor would lead to a more indirect route, compensating each other.

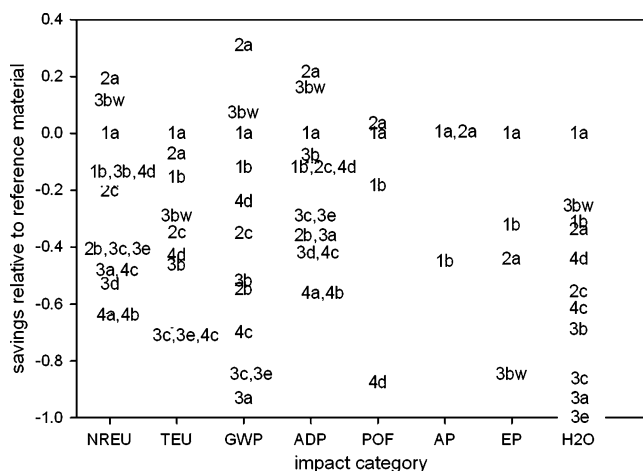


Fig. 2 Savings of Inner Packs relative to reference material (No.1a) for eight impact categories and including one case of PLA with wind credits (No.3bw); system cradle-to-factory gate, including transportation. Note: negative values represent cases with higher environmental impacts than the reference material; materials not shown are outside the range of the graph on the lower end (<-1.0), i.e. worse

Laminates which only partially consist of bio-based films (2a–c, 4c,d) have lower land-use than completely bio-based ones because of biomass cultivation. Films 3a–4b are in the same range, with the exception of 4a, which is the Inner Pack with the highest material input (i.e. heaviest laminate, see Fig. 1). The environmental advantages of laminates containing PLA (e.g. No.3b) or cellulose (e.g. No.2b) can be further enhanced by future energy and material efficiency improvement (see Section 5.1). As shown in Fig. 4, the paper/OPP film (No.2a) scores better (30% for GWP) than the reference materials (films No.1a and 1b) for incineration with energy recovery and approximately comparable for landfilling with landfill gas recovery. One double-layer

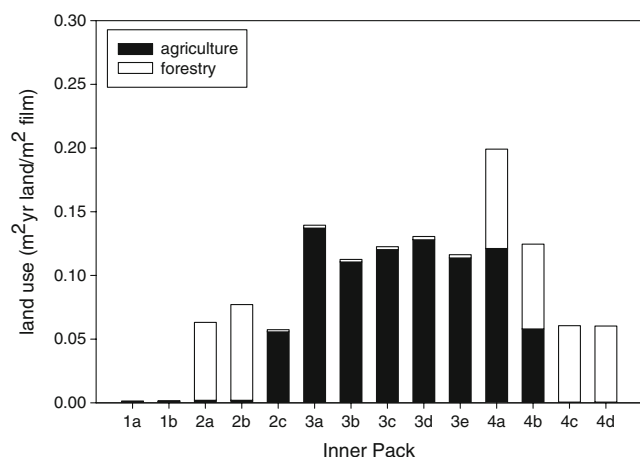


Fig. 3 Agricultural and silvicultural land use of Inner Packs; system cradle-to-factory gate. Note: reference materials have little or no such land use

PLA film (No.3b) scores best for composting and digestion among the biodegradable laminates. Across all materials and waste management options, the global warming impacts are lowest (close to $0.2 \text{ kg CO}_2/\text{m}^2$) for landfilling of the reference materials (No.1a and 1b)¹² and of the paper/OPP film (No.2a), they are slightly higher for incineration with energy recovery of the paper/OPP film (No.2a). The paper/OPP film (No.2a) and the current OPP film (No.1a) are the preferred options in terms of GWP in Europe.

4.2 Outer packs

There are two films that are currently being used as Outer Packs: PE film (No.5a) and OPP film (No.6). As shown in Fig. 5, the PE film scores much worse (10–70%) than the OPP film in all impact categories. Significant environmental improvements could thus be achieved by just replacing the current PE film by the current OPP film. However, the current OPP film (No.6) is not the best option. Focussing on the partially bio-based laminates, the paper/OPP laminate (No.9a), the paper/PE laminate (No.9d) and especially the paper/EVA laminate (No.9h) represent alternatives with a clearly improved environmental performance. In the group of totally bio-based laminates, the thinner bio-based PE film (No.5c) is an interesting alternative for the current PE film (No.5a) because it scores better than the reference material (No.6) in most impact categories (worse only for AP and EP). The bio-based polyesters (No.9e–9g) are a promising option, especially if the impacts regarding photochemical oxidant formation (POF) and eutrophication (EP) can be reduced. As Fig. 5 shows for Outer Packs, the pure PLA film becomes attractive compared to the reference material (No.6) if wind credits are taken into account (No.7w), though not without wind credits (No.7). In terms of land-use, completely bio-based laminates (e.g. No.9b) show higher land-use than partially bio-based laminates (e.g. No.9a) because of biomass cultivation. Those laminates that include bio-based PE (No. 5b,c) or BBP (No. 9e–g), show relatively high land-use, also when comparing with Inner Packs (Fig. 6). The cradle-to-grave analysis shows that the reference OPP film (No.6) does not score best for any waste treatment type. For all waste treatment types, there are several laminates that perform better than the reference material: No.5c, 9a, 9d–h (Fig. 7). For incineration with energy recovery, the films that score best are the bio-based PE film (No.5c) and the paper/EVA laminate (No.9h),

¹² These materials consist of PP, which does not degrade in landfills and therefore releases no emissions during this phase.

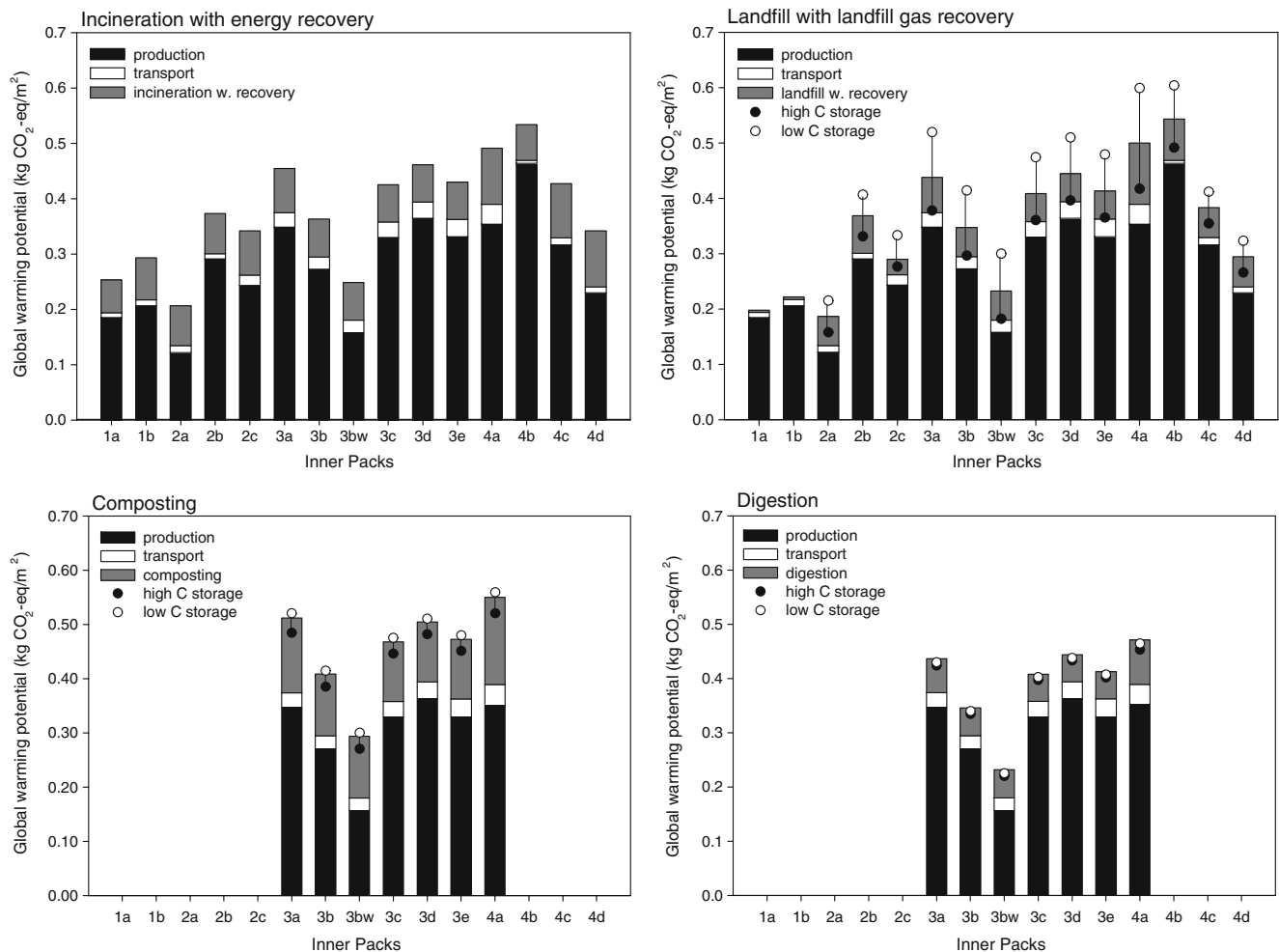


Fig. 4 Cradle-to-grave: Global warming potential for Inner Packs for four waste treatment types: incineration with energy recovery, landfilling with landfill gas recovery, composting and digestion

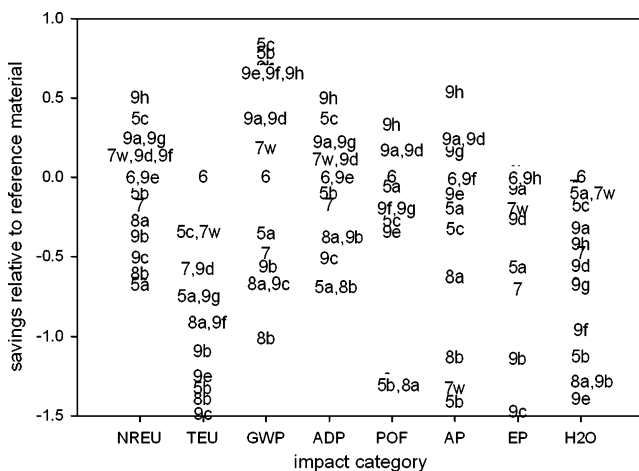


Fig. 5 Savings of Outer Packs relative to reference material (No.6) for eight impact categories and including one case of PLA with wind credits (No.7w); system cradle-to-factory gate, including transportation. Note: negative values represent cases with higher environmental impacts than the reference material; materials not shown are outside the range of the graph on the lower end (<-1.5), i.e. worse

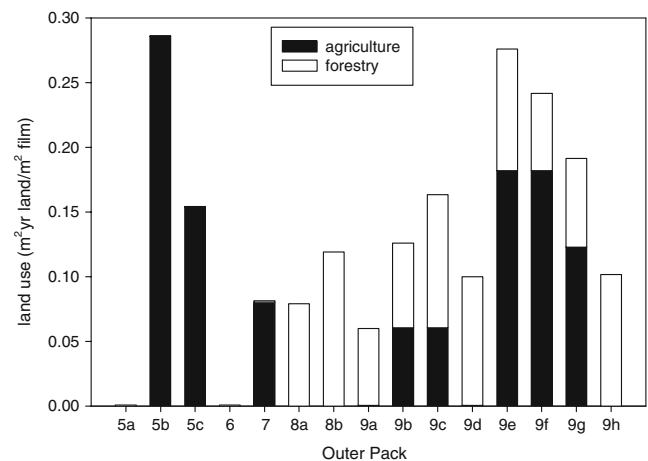


Fig. 6 Agricultural and silvicultural land use of Outer Packs; system cradle-to-factory gate. Note: reference materials have little or no such land use

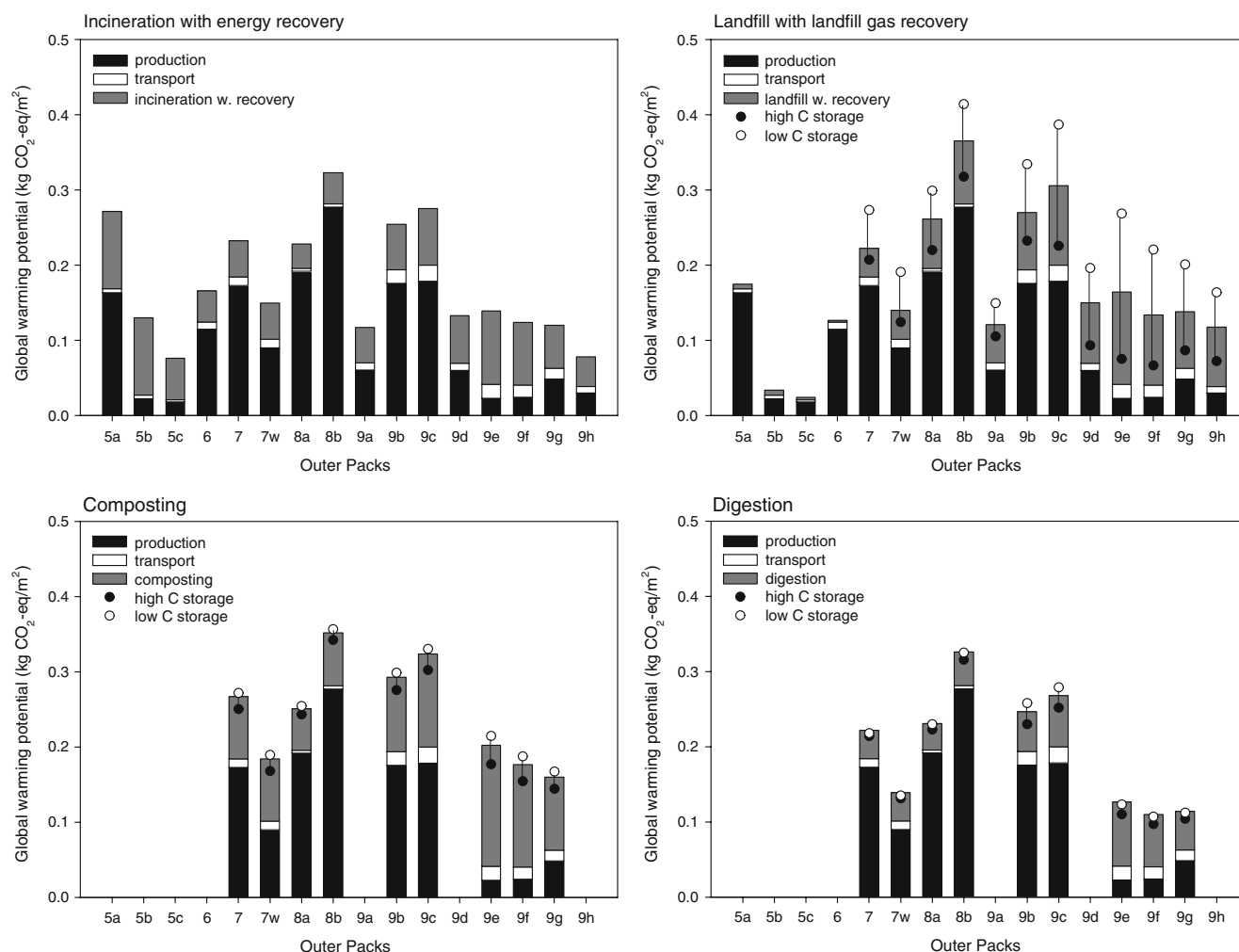


Fig. 7 Cradle-to-grave: Global warming potential for Outer Packs for four waste treatment types: incineration with energy recovery, landfilling with landfill gas recovery, composting and digestion

followed by the bio-based polyester (No.9g) and the paper/OPP laminate (No.9a). For landfilling with landfill gas recovery, the bio-based PE films (No. 5b and 5c) score significantly better than the reference material (No.5a and 6). The paper/OPP laminate (No.9a) and the paper/EVA laminate (No.9h) score as well as the current OPP film (No.6). None of the reference materials are biodegradable, so composting and digestion cannot be compared relative to the current materials. For composting and digestion, the bio-based polyesters (No.9e–9g) score best. When also taking land-use into account, the partially bio-based laminates (No.9a,9h,9d) score best. Overall, the environmentally most attractive Outer Packs are bio-based PE¹³ (No.5c), paper/PP laminate (No.9a), paper/EVA (No.9h), paper/bio-based polyester (No.9g) and to a somewhat lesser extent also paper/petrochemical PE (No.9d). Incineration

¹³ Bio-based polyethylene (and bio-based ethylene) is currently not on the market, but Braskem and Dow are building plants for commercial production in 2009 and 2011 respectively (Schut 2008).

with energy recovery is the best waste treatment option for non-degradable materials. For biodegradable materials, digestion is a better waste management option than composting in terms of global warming potential and non-renewable energy use and it is slightly better than incineration with energy recovery of the same materials.

5 Sensitivity analysis and discussion

5.1 Technology maturity

The production of petrochemical materials has made significant progress over the past 100 years, but the production of some bio-based materials (e.g. PLA and BBP) is relatively new. For the production of bio-based materials, there is a significant potential to reduce the environmental impacts in the future with increasing technology maturity both at the material production

(granulate) and at the processing (film production) stage. We show this improvement potential by considering future PLA granulate production (PLA-NG¹⁴, Fig. 8) and improved film production for PLA and cellulose. For PLA film production, the future case entails that the energy use for making film from polymer granules as well as the material efficiency (process waste) are assumed to equal that of today's OPP film production from PP granules. For cellulose film production, the potential future energy use for making the cellulose film from pulp was estimated on the basis of that of cellulose fibre production. According to Schmidbauer (1997), non-renewable energy use in Viscose fibre production is approximately 19 MJ/kg in a large-scale plant with a total energy use of 75 MJ/kg, thus including a large share (75%) of renewable energy. To account for differences in scale between cellulose fibre and cellulose film production, for a higher share of non-renewable energy and for important differences in processing technology, we conservatively assume that the non-renewable energy use for cellulose film production in the medium to long term is four times as high as for viscose fibres, i.e. 76 MJ/kg. Figure 8 shows that for PLA and cellulose, future film production significantly improves the global warming potential compared with today's technology. In the case of PLA, when considering wind credits for granulate production (see Section 2.4) and/or future raw material production (PLA-NG), the PLA film (No.3b) becomes advantageous compared with the reference material (No.1a). In the case of cellulose, the future cases are almost as good as the reference materials but the future cellulose film cannot compete with the paper hybrid laminate in this specific application.

5.2 Wind credits for electricity use in film production and conversion

In Section 2.4, we discussed the methodology of accounting for wind credits and showed the effect of buying wind credits at the raw material production stage (PLA). But wind energy credits can be bought by any company, also by film producers. In this section we therefore show the effect of compensating for energy use during film production by means of wind credits.¹⁵ As film producers are closer to the final consumers, they have more potential interest in improving the environmental profile of their films; wind energy credits are therefore more likely to be bought in by companies on the level of film producers and converters

¹⁴ Future PLA granulate production is also referred to as 'next generation' (NG).

¹⁵ In principle, it is even possible for a company to compensate beyond the non-renewable energy use of its own processes through wind credits. However, this case is not considered here.

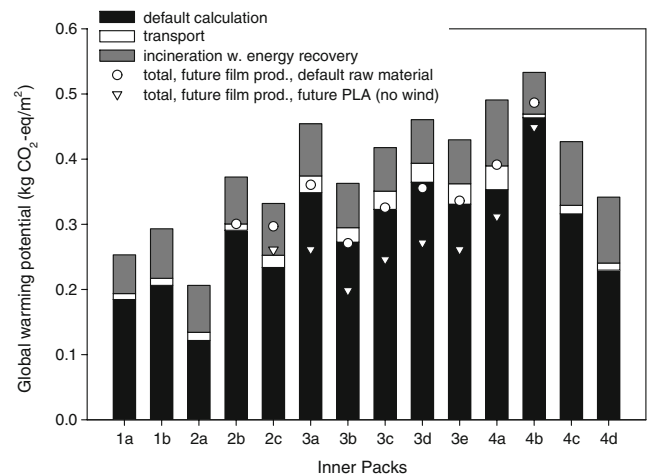


Fig. 8 Global warming potential of laminates assuming future technology levels for film-making of PLA and cellulose: 1) today's technology (all laminates), 2) current raw material production and future film production (PLA and cellulose, ○) and 3) future granulate & future film production (only PLA, ▼); system boundary: cradle-to-grave

(producing e.g. PP film from granulate), and less so by the large-scale producers of petrochemical materials (producing e.g. PP granulate). Figure 9 shows that for the reference material Inner Packs (No.1a and 1b), the environmental score can be improved by wind energy credits for the energy used in film production and lamination, but the hybrid paper film (No.2a) still performs better. For the PLA laminates, wind credits for the film production and lamination & printing stages significantly improve the environmental profile and make it environmentally comparable with the reference material (No.1a). If in addition, wind credits for raw material production are added, the

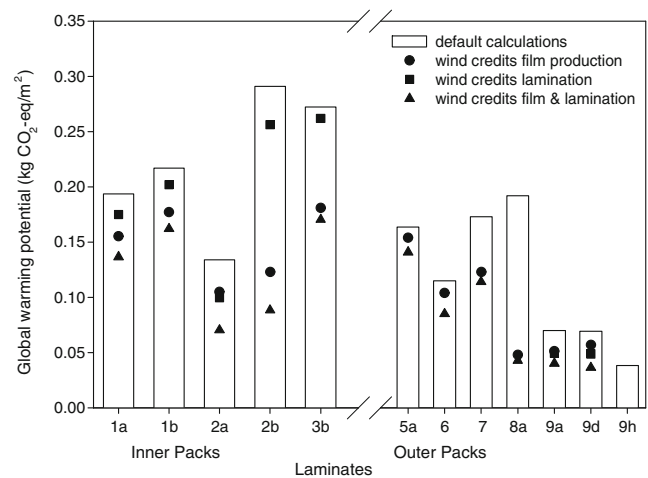


Fig. 9 Global warming potential of wind credits during film production from granulate and/or during lamination; system boundary: cradle-to-factory gate, excluding transportation. Note: films 5a; 6–8a only consist of one material and thus no wind credits for lamination can be assigned

PLA film (No.3b) also outperforms the paper hybrid laminate (No.2a).¹⁶ Wind energy credits to offset electricity use by film producers or suppliers therefore offer environmental advantages as an additional measure but by themselves are not enough for any film or laminate to overtake the best environmental profile of a film or laminate without such credits.

5.3 Waste management

The uncertainties related to the assessment of the waste management stage are very large, given the very wide range of the values reported in literature. These uncertainties concern both carbon storage in the solid phase (i.e. in compost, digestate or stored inside a landfill) and the composition of CO₂ and CH₄ in the gaseous phase (landfill gas, biogas from digestion and CH₄ emissions to the atmosphere). The overall difference between different types of waste-treatment with respect to GWP is rather small for biodegradable laminates and larger for non-degradable laminates where essentially no GHGs are released during landfilling. These differences are entirely due to the degradability (or lack thereof) of the material and as such cannot be reduced. Although the uncertainty regarding the degree of degradation of paper, cellulose, PLA and BBP is large, this uncertainty is not decisive for the conclusions: the difference between the materials in terms of environmental advantages is large enough for the conclusions to still hold (compare Figs. 4 and 7).

6 Conclusions and recommendations

The environmental advantages of novel bio-based materials are sometimes lower than one may expect because of comparatively high energy consumption in one or more of the production stages. This is partly due to less favourable barrier and mechanical properties that result in higher material inputs. The lack of experience and investment in converting these polymers into final products (higher percentage losses during processing than comparable petrochemical polymer gauges, long down-times, old and inefficient machines being used for the current testing phase) also plays an important role. This lack of investment is easily resolved under suitable market conditions. Some of the novel bio-based materials score remarkably well: the paper hybrid Inner Pack (No.2a) offers GHG savings of 30% for cradle-to-factory gate and small advantages for cradle-to-grave relative to the reference material (OPP film, see Fig. 4). Outer Packs consisting of paper and a bio-based

polyester (BBP) offer GHG savings in the order of 60%–80% for cradle-to-factory gate and of 15%–30% for cradle-to-grave (incineration with recovery) relative to the reference material (OPP film, see Figs. 5 and 7). We recommend investigating to which extent options that score well for Outer Packs (bio-based polyethylene to replace petrochemical PE, paper/EVA film (No.9h) and the paper/bio-based polyester laminates (No.9e–9g)) can be applied in suitable combinations also for Inner Packs. Inner and Outer Packs containing PLA film produced using today's technology and excluding wind energy credits (technology perspective) offer no significant environmental advantages, but when future technology for PLA is considered or if wind credits are assigned, PLA laminates become environmentally comparable with the reference material. It is therefore important a) that all decisions fully account for the consequence of choosing the technology perspective or the company perspective and b) that more R&D is carried out towards optimising PLA granulate and film production. Films and laminates containing cellulose produced using today's technology do not show any environmental advantages. This may change in the medium to long-term future, if producing cellulose film on a large scale and/or by using novel technologies. Bio-based polyester (BBP) offers environmental advantages, but leads to higher land-use than other bio-based materials.

Generally, laminates and films (partly) consisting of bio-based polymers offer opportunities for significantly reducing environmental impacts of food packaging. Large variations in land-use are possible depending on the type of bio-based material that is used. The environmental advantages differ depending on the polymer and the final product (Inner vs. Outer Pack). Overall, when introducing bio-based wrappings to replace the current petrochemical material, Outer Packs are more promising than Inner Packs because a) the opportunities are much clearer for this application and b) the product specifications (required barrier properties) are less demanding. Starting with the Outer Packs would also allow producers and converters of bio-based polymers to invest and learn, and therefore offer them the opportunity to reduce the environmental impact even further.

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¹⁶ It should be noted that the results presented in Fig. 9 exclude PLA raw material production with future technology (PLA-NG).

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